Artículo de investigación

Influence of test modes and accuracy of manufacturing a roller cone bit on loading of its elements

Влияние режимов испытаний и точности изготовления шарошечного долота на загруженность его элементов

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Abstract

A technique has been developed for selecting test modes for direct measurement of forces acting on the cutting structure elements of a cone bit during its interaction with the face of hole at a special stand. The optimal intervals of axial loads on the bit and bit rotation frequencies are determined, which allow to obtain an objective picture of the distribution of forces in the equipment of the bit. The results of experimental studies of the load of cutting structures of the cone bits depending on the different heights of cones are presented. It has been established that with an unfavorable combination of the relative position of the cone, even within the tolerance, the axial load acting on one cone can almost double. The research results allow a more reasonable approach to the selection of indicators for the accuracy of production of bits.

Key Words: Accuracy of manufacturing, bit, cone cutting structure, drilling, load, roller cone.

Аннотация

Разработана методика выбора режимов испытаний для проведения непосредственного измерения сил, действующих на элементы вооружения шарошечного долота в процессе его взаимодействия с забоем на специальном стенде. Определены оптимальные интервалы осевых нагрузок на долото и частот вращения долота, позволяющие получить объективную картину распределения сил по вооружению долота. Приведены результаты экспериментальных исследований загруженности вооружения шарошечного долота в зависимости от разновысотности шарошек. Установлено, что при неблагоприятном сочетании взаимного положения шарошек даже в пределах допуска, осевая нагрузка, действующая на одну шарошку, может увеличиваться почти в два раза. Результаты исследований позволяют более обоснованно подходить к назначению показателей точности изготовления долот.

Ключевые слова: бурение, вооружение шарошки, долото, нагрузка, шарошка, точность изготовления.

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Introduction

When drilling deep oil and gas wells, as well as blast holes in mining pits, cone bits are widely used. The bit cones, loaded with axial force from the weight of the drill string or hydraulic force, during its rotation roll over the rock and destroy it. The durability of the cutting structure and supports of cone drill bits depends on many factors, such as axial load on the bit, rotational speed, characteristics of the drilled rocks, properties and composition of the flushing fluid, the design of the bit, the quality of manufacture of its parts, and properties of materials. Roller cone bits work in severe conditions, being exposed to high static and dynamic loads, abrasive and corrosive environments, shocks and vibrations. The durability of the cutting structure of the cones directly destroying the rock largely determines the main indicators of the drilling efficiency. In this regard, a significant number of studies (Belikov etc., 1972; Vinogradov etc., 1977; Mokshin etc., 1971; Simonov etc., 1975) are devoted to issues of depreciation and destruction of the cutting structure. In the process of drilling, the cone bits are rolling over the bottom, and the teeth successively come into contact with the rock, being subjected to a complex force. During the interaction of the tooth with the bottom, the forces acting on the tooth from the side of the destructible rock constantly change, changing the stress state of the tooth material. As a result of longitudinal oscillations of the bit, caused by a number of reasons, the interaction of the teeth with the rock is of shocking nature. In addition, the teeth of the cone cutting structure not only roll over, but also slip along the bottom, which leads to their wear. Analysis of the state of the carbide cutting structure of bits of various designs worked out under field conditions showed that in the process of work there are a wide variety of types of wear and tear (Belyaev, 1977; Pyalchenkov etc., 2016; Bogomolov, 1975; Kirpichnikov, 1981).

The reliability and durability of the drilling tool depend on many design, technological and operational factors, including the magnitude of the forces acting on their elements during operation. The results of the calculation-analytical and experimental methods for determining the load of the working elements of the cutting structure of the cone bits, obtained even at zero or close to zero values of the height differences of the cones, showed a significant loading of the individual sections of the bit (Pyalchenkov etc., 2016; Pyalchenkov, 1983). At the same time, different heights of cones taking place in the practice of bit manufacture will additionally have a significant and adverse effect on the redistribution of the axial load, causing in some cases an even greater degree of overload of individual elements of the bit.

Bench and field studies of the performance of roller cone bits made with varying degrees of deviation of the main geometric parameters from the nominal values have established a negative effect of these deviations on the main performance indicators of the bit. In particular, the results of field studies of several groups of cone bits of various types indicate a significant decrease in the resistance of cones and headway per bit with an increase in the cone height difference. It is noted that with an increase in the hardness of the drilled rocks, the negative effect of different heights on the resistance of the cone supports increases. One of the reasons for the decrease in bit resistance with increasing cone height difference is the uneven distribution of the axial load over the sections of the bit, causing accelerated wear and destruction of cutting elements and supporting units of individual cones.

The question of the effect of different heights on the load of the bit elements has not yet been studied. All known studies are performed only for bits with the milled cutting structure. Attempts have been made to evaluate the effect of different heights on the magnitude of the load acting on the roller bearings of the cone supports of the bit model (Pyalchenkov, 2015). However, probably, due to the complexity of conducting studies using this technique, only one variant of the relative position of the cones was tested, which is clearly not enough to obtain quantitative dependences of the load of the support elements on different heights. In (Postash etc., 1976), the results of a study of the effect of different heights on the loading of sections of a cone bit are presented. The modeling of different heights was carried out due to the vertical movement of the second section of the model relative to the first and third sections in the range from +5 to -5 mm through an interval of 1 mm. The conducted studies allow us to establish a qualitative relationship between the position of one section of the bit relative to others and the vertical load acting on it. But the selected limits of variation of different heights due to the capabilities of the technique are virtually never found in real bits, which reduces the practical value of the results.

Methodology

In order to establish quantitative patterns of the influence of different heights of cones on the load on carbide cutting elements of the bits at a special bench (Comm, 1978; Pyalchenkov, 2015), a batch of bits was tested, the different heights of which varied from 0.34 to 1.28 mm. The tests were carried out using a device that allows measuring the forces perceived by each tooth of each cone of a real bit when it interacts with a non-destructible bottom. For separate registration of efforts acting on the crowns of each cone, the bottom is divided into two sectors, working (measured) sector I and non-working sector II (Figure 1). When the bit rotates along the bottom, the cones are in contact with the ring-shaped inserts of the working sector I of the bottom.

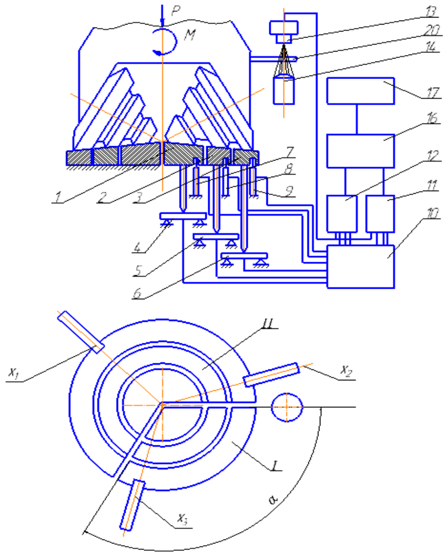

Figure 1. Schematic diagram of the measurement and registration of forces acting on the teeth of the cones: 1,2,3- ring-shaped bottom of the working sector; 4,5,6,7,- tensometric beams; 7,8,9-inserts; 10-amp; 11,12- oscilloscopes; 16,17- conversion equipment; X1. X2, X3 – axes of the cones.

To implement this method, a special bench was designed and manufactured to rotate the test bit along the bottom of the measuring device. The axial load on the bit can smoothly vary from 0 to 200 kN, which allows testing bits of various sizes with axial loads close to or equal to the working loads, depending on the size of the bit under study. The drive of the bench provides a change in the angular velocity of the bit from 0.16 to 11.34 s-1, thereby reproducing the conditions of rotary drilling. The vertical components of the reactions of the interaction of the cone teeth with the bottom parallel to the axis of rotation of the bit deform the tensometric beams 4, 5, 6. Sensitive elements for registering the tangential components are inserts 7, 8, 9. Deformations of beams and inserts are converted by sensors into electrical signals proportional to the values of the axial and tangential reactions of the interaction of the bit cones with the bottom, which are recorded by oscilloscopes 11, 12 and processed using special equipment. The studies were carried out on bits Sh215, 9K-PV intended for drilling in hard rocks with cleaning the bottom with compressed air or an air-water mixture. The permissible axial maximum load on the bit is 250 kN, and the recommended angular bit speeds are from 0.8 to 1.2 s-1. The choice of this type of bit is due to the fact that the cone cutting structure of this bit is made of carbide teeth of the same type with a hemispherical head, which eliminates the possible influence of the shape of the teeth on the parameters studied. In addition, the supporting units of the cones of these bits are made according to a widespread scheme: a large roller bearing - a ball lock bearing - a small roller bearing. This extends the results of studies of these bits to bits of other types with the same pattern of supporting units. Figure 2 shows the cone cutting structure of the studied bit and the scheme for differentiating the bottom along the crowns.

Analyzing the oscillograms of the time variation of the axial components of the force of interaction between the teeth of the bit cone and the bottom (Pyalchenkov, 1983; Pyalchenkov, 2015), it can be established that the processes of change in reactions are random stationary periodic processes. On the oscillogram, peaks of axial forces acting on the crowns are periodically repeated, and the periods of the processes depend on the number of teeth on the crowns.

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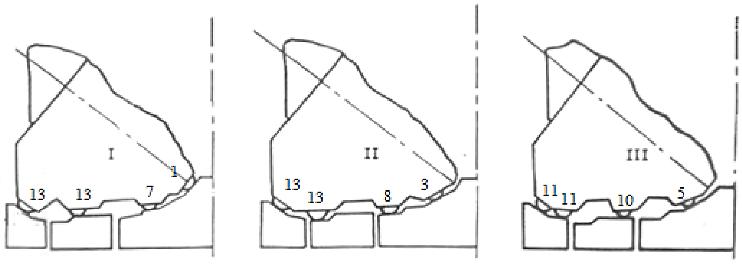

Figure 2. Diagram of the cutting structure of roller cone bits Sh215, 9K-PV and the diagram for differentiating the bottom along the crowns (I, II, III - cone numbers; 13, 13, 7, 1 …- number of teeth on the crowns).

Let us consider the diagram of interaction of the cutting structure of one crown with the bottom (Figure 3). There are two extreme cases of the interaction of the cutting structure of the crown with the bottom. At time t1, the crown takes position 1, when the vertical axis of symmetry of the crown divides the angle between adjacent teeth almost in half. At this moment, one tooth comes out of contact with the bottom and the next comes into contact with the bottom, while the axial component of the force P acting on the crown takes a minimum value and can be zero if one of the teeth has already come out of contact with the bottom, and the next tooth has not yet made contact. At time t2, the crown takes position 2, when the vertical axis of symmetry of the crown coincides with the axis of one of the cutting structure tooth. At this moment, the maximum axial load perceived by one tooth acts on the crown. In addition to the axial components of the reactions of the interaction of the teeth with the bottom, there are also tangential components F lying in a plane perpendicular to the axis of rotation of the bit. When conducting experimental studies of the load of the carbide cutting structure of the bit, the main attention was paid to studying the distribution of the axial force acting on the bit among the elements of the cone cutting structure. The study of the distribution of torque over the cutting structure of the bit was carried out only when determining the forces acting on each tooth of the cone cutting structure. This is due to the fact that the magnitude of the torque acting on the bit depends, other things equal, on the magnitude of the axial force acting on the bit. Therefore, it can be assumed that the magnitudes of the tangential components of the forces acting on the crowns and individual teeth of the cones depend on the values of the axial forces. In addition, when drilling hard rocks with bits made without mixing the axes of the cones in plan, the torques on the bit are relatively small, and the influence of the tangential components of the forces on the durability of the teeth of the cutting structure will be significantly less than the axial components.

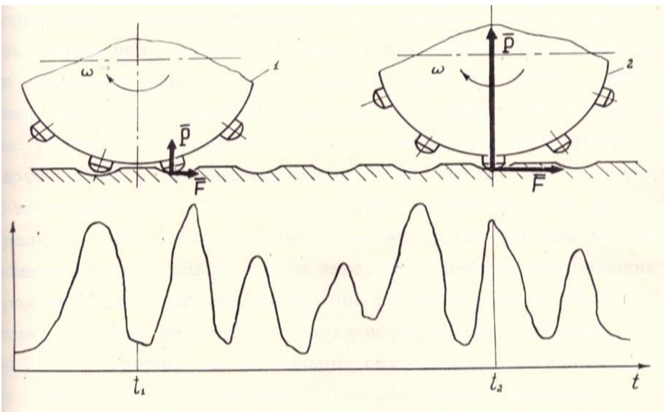

Figure 3 Diagram of the crown cutting structure interaction with the bottom.

Results

To establish the influence of the test modes on the nature of the axial load distribution among the cutting elements, tests were carried out at various axial loads and bit angular speeds. The studies were carried out on bits where the maximum difference in the level of the cone arrangement in the direction of the axis of the thread of the bit relative to the box shoulder (different height) did not exceed 0.2 mm. The axial load on the bit was taken equal to 20, 40, 80, 120 and 160 kN. For each value of the axial load, tests were conducted at angular bit speeds of 1.31 s-1, 3.30 s-1, 5.65 s-1, 11.31 s-1. The tests showed that with an increase in the load on the bit, the axial force on each crown of each cone increases proportionally, and the proportionality coefficients for all the crowns in the studied force range are close to the proportionality coefficient of the increase in the load on the bit. However, the rate of increase in the axial load at different crowns is slightly different, i.e. with an increase in the axial load on the bit, it is redistributed between the crowns. To find out the nature of this redistribution, we determine the relative immersion of all the crowns of the cones, using the dependence:

$$P_{i0} = \frac{P_i}{\sum_{i=1}^{k} P_i} * 100\% \qquad (1)$$

where P_{i0} - relative average load on the i-th crown in %;
p_i - absolute average load on the i-th crown in kN;
k- number of crowns of all bit cones.

Calculations showed that the relative load of the crowns changes when the axial load on the bit changes.

These changes are especially significant at small (up to 40 ... 60 kN) loads on the bit. With a further increase in the axial load on the bit, the change in the relative load of the crowns of the cones slows down and with an axial load of more than 80 ... 100 kN, its redistribution between the crowns of the cones is virtually not observed. The greatest non-uniformity of the axial load distribution along the crowns of the cones is observed at small values of the load. With an increase in the axial load on the bit, there is a tendency to equalize the relative load of various crowns of the cones. So, with axial loads of 20, 40, 80, 120 and 160 kN on the bit, the relative load of the peripheral crown of the first cone is 16.4%, 13.5%, 10.6% and 9.7%, respectively. For the peripheral crown of the second cone, these values will be 4.9%, 7.3%, 8.7%, 10.1% and 10.3%, the relative load of the peripheral crown of the third cone is 7.2%, 8.6%, 10.8%, 11.3%, 11.2%. From these data, it is clear that there is not only a quantitative, but also a qualitative redistribution of the load. So, with an axial load on the bit equal to 20 kN, the peripheral crowns of the three cones according to their degree of loading will be in a row I>III>II. If we take the relative load of the peripheral crown of the second cone as one, then the load of the peripheral crowns of cones I and III will be 3.35 and 1.47, respectively. With an axial load on the bit of 160 kN, a row of loads of the peripheral crowns of the cones will look like III>II>I and, if we take the load of the peripheral crowns of the first cone as one, then the load of the peripheral crowns of the third and second cones will be 1.15 and 1.06. A similar picture is observed when analyzing the load of the middle and top crowns of the cones. Redistribution of the load occurs not only between the cones, but also between the crowns of one cone. For the second cone, with an axial load on the bit of 20 kN, the vertex crown is the most loaded, perceiving 14.3% of the total load on the bit, and the peripheral crown is the least loaded, the relative load of which is 4.9%. However, with an axial load on the bit of 160 kN, the middle crown becomes the most loaded, perceiving 12.5% of the total load, and the vertex crown is the least loaded, the load on which is 8.7%. From the above analysis it follows that in order to obtain reliable data on the distribution of axial load on each crown of each cone of a bit of a given size, it is necessary to conduct tests with an axial load on the bit of at least 80 ... 100 kN.

To determine the influence of the bit angular velocity on the nature of the load distribution, tests were carried out with an axial load on the bit of 80 kN and bit angular velocities of 1.31 s-1, 3.30 s-1, 5.65 s-1, 11.31 s-1. With an almost tenfold change in the angular velocity of the bit, the change in the load of the crowns of the cones is insignificant and does not exceed the experimental error. There are no regularities in these changes; therefore, we can conclude that a change in the angular velocity of the bit in the studied range has virtually no effect on the distribution of the axial load along the crowns of the bit cone. Therefore, it is possible to choose the most convenient test mode for carrying out certain studies without significant restrictions.

The value of the height difference was determined as the absolute value of the maximum difference in the levels of arrangement of the cones relative to the box shoulder of the thread, measured along the peripheral rows of teeth. To eliminate the error during the tests, when transitioning from experiment to experiment, the bits were selected with the same radial and axial backlash in the cones. Obviously, the relative position of the three cones along the axis of the thread of the bit cannot be exhaustively characterized by one parameter - different heights. Therefore, for the bits intended for research, the relative position of the cones

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was determined by two parameters - X1 and X2. Here, X1 - the difference in the levels of the first and second cones relative to the box shoulder, X2- the difference in the levels of the second and third cones. The position of the second cone was chosen as the reference point, and if the first or third cone is offset relative to the second in the direction of the bottom, then the corresponding parameter has a positive sign, if the offset is in the opposite direction, then the sign is negative. To find out the influence of the position of the cones relative to the box shoulder on the distribution of the axial load along the crowns of each cone, it is necessary to establish dependences of the form:

$$P_i = F_i(X_1, X_2) \qquad (2)$$

where, P_i average axial load acting on the i-th crown.

To obtain dependences (2) directly from the experiment, it is necessary to conduct several series of tests, leaving the values of one parameter constant in one series and changing the values of the second parameter. However, the results of measuring bits showed that the parameters X1 and X2 are random and independent values, and it is almost impossible to select the number of bits necessary for conducting research with predetermined combinations of parameters X1 and X2. Therefore, we chose a different path to solve the problem. For the bits selected for research, the values of different heights varied from 0.34 to 1.28 mm, and the combination of parameters X1 and X2 is arbitrary and diverse. The selected bits were tested with an axial load on the bit of 80 kN and an angular velocity of the bit of 3.3 s-1. As a result of the study, Pi values are obtained corresponding to the relative average load as a percentage of the total axial load of all the bit crowns at different relative positions of the cutters. The dependences of the form (2) were determined from the obtained experimental data for each crown using the mathematical apparatus of regression analysis. Since the form of the function Pi is not known in advance, we chose it in the form of a polynomial segment:

$$\mathrm{Pi} = B_{0i} + B_{1i} * X_1 + B_{2i} * X_2 + B_{3i} * X_1^2 + B_{4i} * X_2^2$$

The regression coefficients B_i were estimated using the least squares method. The regression coefficients were calculated for various degrees of the polynomial. The verification of the adequacy of the obtained mathematical models with experimental data was carried out by the F-test. The significance of the regression coefficients was evaluated by the Student's t-test. As a result of the calculations, it was found that the change in the load of the peripheral crowns depending on the position of the cones is adequate at a confidence level of 0.95 and is described by polynomials of the third degree. So, for the peripheral crown of the first cone, this dependence has the form:

$$P_1 = 10{,}21 + 4{,}65\, X_1 - 1{,}83\, X_2 + 1{,}9 X_1^2 - 0{,}9 X_2^2 + 4{,}03 X_1^3$$

The dependence of the load on the middle and vertex crowns of the same cone is described by the following polynomials:

$$\mathrm{P}_2 = 20{,}32 + 1{,}23\mathrm{X}_1 - 0{,}53\mathrm{X}_2 + 1{,}45\mathrm{X}_1^3 - 0{,}82\mathrm{X}_2^3$$

$$\mathrm{P}_3 = 13{,}84 + 1{,}07\mathrm{X}_1 - 0{,}69\,\mathrm{X}_2$$

Similar dependences were obtained for the remaining bit cones.

Discussion

Based on the calculated mathematical models of changing Pi from X1 and X2, graphical dependences of the relative load of all the crowns of the first cone from X1 at X2 = 0 were constructed (Figure 4).

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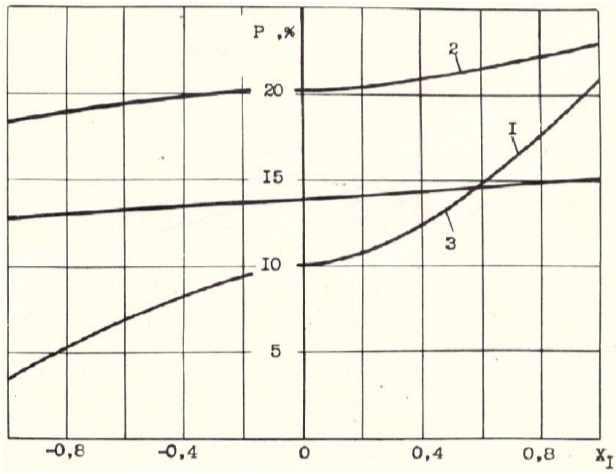

Figure 4. Dependences of the relative load of the crowns of the first cone of the bit Sh215,9KPV on the relative position of the cones at P= 80 kN, ώ=3.3 s-1 (1-peripheral crown, 2- middle crown, 3- vertex crown, X2=0)

The greatest influence of the mutual position of the cones relative to the box shoulder has on the load of the peripheral crown. This, obviously, can be explained by the design of the cutting structure of the cones. The fact is that for all three cones, peripheral crowns destroy the same ring-shaped bottom section, while each other crown destroys its own ring-shaped bottom section. Therefore, the largest share of destruction of the peripheral bottom section falls on the peripheral crown of the cone that protrudes relative to the other two cones towards the bottom.

Summing up the expressions P1, P2, P3, we obtain the dependence of the relative load of the first cone on its position relative to the second and third cones:

$$P_I = 44{,}37 + 6{,}95X_1 - 3.05X_2 + 1{,}9X_1^2 - 0{,}9X_2^2 + 5{,}48X_1^3 - 2{,}53X_2^3$$

Figure 5 shows a graphical interpretation of dependence (7) with a change in X1 and X2 in the range from -1 mm to +1 mm.

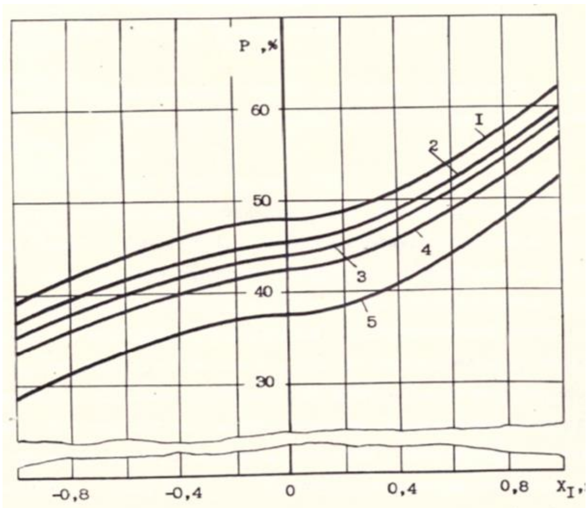

Figure 5. Dependences of the relative load of the first cone of the bit Sh215,9K-PV on the relative position of the cones at P= 80 kN, ώ=3.3 s-1
(1-X2=-1mm; 2-X2=-0,5 mm; 3-X2=0 mm; 4- X2=+0,5 mm; 5-X2=+1 mm.)

Conclusions

It is easy to see that with the most unfavorable combinations of X1 and X2 changing even within the tolerance for different cone heights, the load acting on one of the cones of the Sh215,9K-PV bit can almost double. This, in turn, will lead to an increase in the wear and destruction rate of the cutting structure and elements of the roller cone support assembly, and, as a result, to a decrease in the durability of the bit as a whole. The presented results of the study of the effect of cones of different heights on the distribution of axial load among the carbide elements of roller cone bits are in full agreement with the results of field studies on the impact of accuracy of their manufacture on performance indicators of bits. They once again confirm the importance of the task of reducing the difference in height of the cones and a more reasonable designation of the tolerance on its value, which, undoubtedly, will significantly increase the performance of cone bits.

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